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Application

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**Reconfigurable Thin Film Filter Based DWDM Devices for
Reconfigurable Add-Drop Optical Systems**

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Reconfigurable Thin Film Filter Based DWDM Devices for Reconfigurable Add-Drop Optical Systems

BACKGROUND INFORMATION

5 Field of the Invention

The invention relates generally to the field of optics, and more particularly to optical add-drop multiplexers.

Description of Related Art

Reconfigurable optical add-drop multiplexers (ROADM) have become
10 increasingly popular due to the emergence of dynamic networks. A service provider seeks the flexibility to add or drop any wavelength at any client site/node, which stimulates the development in the areas of tunable filters (TF), tunable laser sources (TLS) and reconfigurable blocking filters (RBF). Current solutions tend to be expensive while yielding mediocre performance. The optical industry remains years away from
15 attaining an optimal design and manufacture solution that provides full reconfigurability at a low cost for next generation of optical networks.

In the interim, semi-reconfigurability solutions that are relatively inexpensive provide attractive alternatives when network carriers desire to contain costs. Two conventional designs of wavelength channel switching are commonly adopted. In a first
20 approach, a transmissive structure employs a wavelength demultiplexer (demux), a wavelength multiplexer (mux), and an array of 2x2 fiber optical switches for directing a light beam to a desired path. However, the use of multiple discrete subcomponents

renders this approach impractical since it causes a high-insertion loss as well as the high cost of using multiple discrete subcomponents.

In a second approach, the filtering and switching functions are integrated on a single device. An example of the integrated functions is a thin film based 2x2 add-drop fiber optical switch. One shortcoming of this device structure is that it does not produce a hitless feature, which is a desirable function for reconfigurability. The term "hitless" in this context means that there is no interruption or negligible interruption in the passage of express or non-drop channels when another channel is transitioning from drop to non-drop or non-drop or drop.

Accordingly, it is desirable to have a reconfigurable optical device that has a hitless switch capability.

SUMMARY OF THE INVENTION

The present invention describes a reconfigurable thin film based dense wavelength division multiplexing (DWDM) device for hitless switching of wavelengths by employing a reconfigurable filtering device. The reconfigurable filtering device is based on a mechanical switching of a filtering chip which has a thin film coated on a first one-half on a first face for interference wavelength filtering and has a gold-mirror coated on a second one-half of the first face for high reflection.

A reconfigurable thin film filter (TFF) based dense wavelength division multiplexing (DWDM) device, comprises a dual fiber collimator having an input port for receiving an input optical signal and a reflection output port; a single fiber collimator

having a transmission output port; and a thin film filter located between the dual fiber collimator and the single fiber collimator, the thin film filter having a first face and a second face, the first face of the thin film filter having an upper one-half and a lower one-half, the lower one-half of the first face in the thin film filter being coated with a reflective material.

In addition, the reconfigurable thin film based DWDM device can be cascaded for designing a reconfigurable add-drop fiber optical system that is capable of either dropping or expressly passing selected wavelengths.

Advantageously, the present invention is polarization insensitive. It produces an insertion loss that is comparable to a conventional thin film filter device. Moreover, the present invention advantageously provides a practical low-cost reconfigurable solution.

Other structures and methods are disclosed in the detailed description below. This summary does not purport to define the invention. The invention is defined by the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a structural diagram illustrating a first embodiment of a reconfigurable thin film filter based dense wavelength division multiplexing device in a pass-through state position in accordance with the present invention.

FIG. 2 is a structural diagram illustrating the first embodiment of a reconfigurable thin film filter based dense wavelength division multiplexing device in a blocking state position in accordance with the present invention.

FIG. 3 is a structural diagram illustrating the first embodiment of a reconfigurable thin film filter based dense wavelength division multiplexing device in a transient state position in accordance with the present invention.

FIG. 4 is a structural diagram illustrating a cross-junction in the first embodiment of the reconfigurable thin film filter based dense wavelength division multiplexing device in the transient state position in accordance with the present invention.

FIG. 5 is an architectural diagram illustrating a reconfigurable thin film filter based dense wavelength division multiplexing system in accordance with the present invention.

FIG. 6 is a structural diagram illustrating a second embodiment of a reconfigurable thin film filter based dense wavelength division multiplexing device in accordance with the present invention.

FIG. 7 is an architectural diagram illustrating an alternative embodiment of a reconfigurable thin film filter based dense wavelength division multiplexing system in accordance with the present invention.

FIGS. 8A-8C are graphical diagrams illustrating an example of the reconfigurable dense wavelength division multiplexing device in the pass-through state position in accordance with the present invention.

FIGS. 9A-9C are graphical diagrams illustrating an example of the reconfigurable dense wavelength division multiplexing device in the blocking state position in accordance with the present invention.

FIGS. 10A-10C are graphical diagrams illustrating an example of the reconfigurable dense wavelength division multiplexing device in the transient state position in accordance with the present invention.

FIGS. 11A-11C are graphical diagrams illustrating experimental results on the traces of the transmitted and reflected signals in accordance with the present invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Referring now to FIG. 1, there is shown a structural diagram illustrating a reconfigurable thin film filter based dense wavelength division multiplexing device (TFF DWDM) 10 in a pass-through state position. The TFF DWDM device 10 comprises a dual fiber (two-fiber) collimator 11, a single fiber (one-fiber) collimator 12, and a thin film filter mirror (TFFM) chip 13. The dual fiber collimator 11, which is well-known in the art, has a dual fiber tip with a graded index (GRIN) lens (not separately shown) so that a first fiber in the dual fiber collimator 11 functions as an input port 14 for receiving an input optical signal and a second fiber in the dual fiber collimator 11 functions as a reflection output port 15. The single fiber collimator 12 has a single fiber tip with a GRIN lens (not separately shown) for correcting a transmission output port 16 through a transmission window of the TFFM chip 13. The TFFM chip 13 has a first face and a second face in which the first face has an upper one-half and a lower one-half. The surface area of the upper one-half in the first face of the TFFM chip 13 is coated with a thin film 32 for transmission of a specific wavelength while the lower one-half in the first face of the TFFM chip 13 is coated with a reflective material 17, such as gold, for reflecting all light back through the dual fiber collimator 11 to the reflection output port

15. One of ordinary skill in the art should recognize that the upper one-half and the lower one-half in the first face of the TFFM chip 13 is intended as an illustration. Other ratios of dividing the upper section and the lower section in the first face of the TFFM chip 13 can be practiced without departing from the spirit of the present invention. It is also
5 apparent to one of skill in the art that the upper one-half in the first face of the TFFM chip 13 could be coated with a reflective material, while the lower one-half in the first face of the TFFM chip 13 could be thin film coated.

In the pass-through position (FIG. 1), the mechanical relay 18 positions the upper one-half in the first face of the TFFM chip 13 at a position y 19 so that an incoming light
10 beam passes through the dual collimator 11, through the TFFM chip 13, through the single fiber collimator 12 and to the transmission output port 16. The upper one-half in the first face of the TFFM chip 13 is coated with a thin film 32 so that the incoming light beam passes through to the transmission output port 16. When the apparatus 10 receives
15 an incoming optical signal comprising one or more wavelengths that are not intended to be dropped, the mechanical relay 18 moves the TFFM chip 13 in the position y 19 (FIG. 1) such that the one or more wavelengths may pass through expressly.

As shown in FIG. 2, there is a structural diagram illustrating a reconfigurable thin film filter based dense wavelength division multiplexing device in a blocking state position. The mechanical relay 18 moves the TFFM chip 13 to a position z 21 such that
20 an incoming light beam travels through the input port 14, propagates through the dual collimator 11, projects onto the reflective material 17 of the TFFM chip 13, and reflects

from the surface of the reflective material 15 back through the dual fiber collimator 11 and to the reflection output port 15.

The process of making the TFFM chip 13 is to coat one-half in a first face of a thin film filter (TFF) with thin film that allows transmission of a specific channel wavelength, followed by the placement of the TFFM chip 13 into a chamber for gold coating the other one-half in the first face of the thin film filter. Preferably, the thickness of the gold coating should be the same as the wavelength of the specific channel, which is designed for transmission for the TFF. This is significant to produce a hitless switching feature in the TFF DWDM device 10, which is affected by the chosen thickness of the gold coating in the TFFM chip 13.

In the switch structure, the position of the TFFM chip 13 is operated by the mechanical relay 18. The mechanical relay 18 is controlled by, for example, a circuit board (not shown) or alternatively by manual operation. The free space optical alignment for each component can be done simply for a TFF device. The mechanical relay 18 has two main positions: at position y 19 (FIG. 1), the mechanical relay 18 moves the TFFM chip 13 to where the input light passes through the thin film 32 of the TFFM chip 13 and exits through the single fiber collimator 12 to the single fiber output port transmission 16; at position z 21 (FIG. 2), the mechanical relay 18 moves the TFFM 13 to where the input light is reflected by the reflective material (e.g. gold mirror) 17 and is reflected back through the dual fiber collimator 11 to the reflection output port 15. The switching time is typically in the milliseconds range.

The TFF DWDM device 10 operates between these two states, a pass-through state (FIG. 1) or a blocking state (FIG. 2). A third state is possible, though not desirable, when the TFFM chip 13 is in a transient state position, as illustrated in FIGS. 3 and 4. The TFFM chip 13 is in the transient state when a light beam from the input optical signal projects from the dual fiber collimator 11 onto the TFFM chip 13 such that a portion of the light beam hits the area coated with the thin film 32 while the other portion of the light beam hits the reflective material 17. As shown in FIG. 4, an input light 43 projects a partial beam 41 and a partial beam 42 at a cross junction 31 in which the partial light 41 hits the thin film coating 32 and the partial light 42 hits the reflective coated material 17. A signal interference could occur while the TFFM 13 is in the transient position where the partial beam 42 reflected from the reflective coated material 17 and the partial beam 41 intercepting the thin film filter area 32 such that the partial beams 41 and 42 may interfere with one another.

The angle θ denotes an incident angle of light, which is typically near 90 degrees where an input light beam is projected. When the light beam projects at the cross junction 31, the first partial input light beam 41 projects onto the upper one-half of the first face which is coated with the thin film 32, while the second partial input light beam 42 projects onto the lower one-half of the first face which is coated with a reflective material 17. The first partial light beam 41 carries a phase differential from the second partial light beam 42. There could also be interference created between the first partial light beam 41 and the second partial light beam 42. In the worst case, the interference

between the first partial light beam 41 and the second partial light beam 42 may cause the first partial light beam 41 to cancel out the second partial light beam 42.

Equation 1 below shows the mathematical relationship between the thickness, t , of the reflective material 17 and the effectiveness of the hitless switching.

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$$t(\sin\theta) = n\lambda \quad \text{Eq. (1)}$$

if $n = 0, 1, 2, \dots$ $I = I_{\max} = I_0$

If $n = \frac{1}{2}$ $I = I_{\min} = 0$

The angel θ is the incident angle, as shown in FIG. 4. The parameter n dictates
10 the thickness, t , of the reflective material 17. The parameter n is preferably selected to be an integer number for producing the maximum intensity of light, as indicated below.

If $n = 1, 2, 3$, or any integer number, the intensity of light will be at maximum, with a constructive interference.

15 If $n = 0.5, 1.5, 2.5$, etc., the intensity of light will be at minimum intensity, with a destructive interference.

When the condition of $t(\sin\theta) = n\lambda$ (where $n = 0, 1, 2$, or $3, \dots$) is met, the two partial beams 41 and 42 will interfere constructively with no loss, where t represents the thickness of the reflective material 17 and λ represents the wavelength. If this condition
20 is satisfied, the reconfigurable thin film filter based dense wavelength division multiplexing device 10 will produce a hitless switching during the transition between the pass-through state and the blocking state in the transient potion (FIGS. 3 and 4).

FIG. 5 is an architectural diagram illustrating a reconfigurable thin film filter based dense wavelength division multiplexing system 50 in accordance with the present

invention. By cascading multiple DWDM devices together, the system 50 operates as multi-wavelength add-drop modules to achieve a flexible combination of whether to drop or express pass-through multiple wavelengths. The system 50, as shown in this embodiment, has four TFF DWDM devices 51, 52, 53, and 54. The first TFF DWDM device 51 can either drop or express pass-through the wavelength λ_1 55. If the wavelength λ_1 55 is express passed-through, it is directed to the second TFF DWDM 52 together with other wavelengths $\neq \lambda_1$. Secondly, the second DWDM device 52 can either drop or express pass-through the wavelength λ_2 56. If the wavelength λ_2 56 is express passed-through, it is directed to the third TFF DWDM 53 together with other wavelengths $\neq \lambda_2$. Thirdly, the third DWDM device 53 can either drop or express pass-through the wavelength λ_3 57. If the wavelength λ_3 57 is express passed-through, it is directed to the fourth TFF DWDM 54 together with other wavelengths $\neq \lambda_3$. Fourthly, the fourth DWDM device 54 can either drop or express pass-through the wavelength λ_4 58 to an output 59. The reconfigurable thin film filter based dense wavelength division multiplexing system 50 operates with a hitless feature in that the dropping of one or more wavelengths at a particular channel does not affect the transitioning on the express channel path.

FIG. 6 is a structural diagram illustrating a second embodiment of a reconfigurable thin film filter based dense wavelength division multiplexing device (TFF DWDM) 60 in accordance with the present invention. The TFF DWDM device 60 provides the capability to add a channel or wavelength through an input add port 61, propagating through a second dual fiber collimator 65, the upper one-half in the first face

(or the thin film 32) of the TFFM chip 13, the dual fiber collimator 11 and to an output add (or reflection port 62). Other operations of the TFF DWDM 60 operates similar to the TFF DWDM device 10 as described in FIGS. 1, 2 and 3 with the reference to the dual fiber collimator 11 as a first dual fiber collimator 11.

5 FIG. 7 is an architectural diagram illustrating an alternative embodiment of a reconfigurable thin film filter based dense wavelength division multiplexing system 70 in accordance with the present invention. By cascading multiple DWDM devices together, the system 70 operates as multi-wavelength add-drop modules to achieve a flexible combination of whether to add, drop or express pass-through multiple wavelengths. The
10 system 70, as shown in this embodiment, has four TFF DWDM devices 51, 52, 53, and 54. The first TFF DWDM device 51 can either drop, add or express pass-through the wavelength λ_1 55. If the wavelength λ_1 55 is express passed-through, it is directed to the second TFF DWDM 52 together with other wavelengths $\neq \lambda_1$. In addition, if the wavelength λ_1 55 is dropped, the wavelength λ_1 55 can be added back through the add
15 port 75 for propagating through the first TFF DWDM 51 to the second TFF DWDM 52. Secondly, the second DWDM device 52 can either drop, add or express pass-through the wavelength λ_2 56. If the wavelength λ_2 56 is express passed-through, it is directed to the third TFF DWDM 53 together with other wavelengths $\neq \lambda_2$. In addition, if the wavelength λ_2 56 is dropped, the wavelength λ_2 56 can be added back through the add
20 port 76 for propagating through the second TFF DWDM 52 to the third TFF DWDM 53. Thirdly, the third DWDM device 53 can either drop, add or express pass-through the wavelength λ_3 57. If the wavelength λ_3 57 is express passed-through, it is directed to the

fourth TFF DWDM 54 together with other wavelengths $\neq \lambda_3$. In addition, if the wavelength λ_3 57 is dropped, the wavelength λ_3 57 can be added back through the add port 77 for propagating through the third TFF DWDM 53 to the fourth TFF DWDM 54. Fourthly, the fourth DWDM device 54 can either drop, add or express pass-through the wavelength λ_4 58. In addition, if the wavelength λ_4 58 is dropped, the wavelength λ_4 58 can be added back through the add port 78 for propagating through the fourth TFF DWDM 54 to the output 59. The reconfigurable thin film filter based dense wavelength division multiplexing system 70 operates with a hitless feature in that the dropping of one or more wavelengths at a particular channel does not affect the transitioning on the express channel path.

FIGS. 8A-8C are graphical diagrams illustrating an example of the reconfigurable dense wavelength division multiplexing device in the pass-through state position in accordance with the present invention. In this embodiment as shown in FIG. 8A, the thin film filter mirror chip 13 is implemented with a TFF 13a and the reflective material 17 is implemented with a gold film 17a. With the mechanical relay 18 holding the TFF 13a in the position y 19, the input optical signal comprising a plurality of wavelength channels $\lambda_1, \lambda_2, \dots, \lambda_n$ enters the input port 14, through the dual fiber collimator 11. The TFF 13a passes a single wavelength λ_d through the single fiber collimator 12 to the transmission output port 16. There is no light signal of wavelength λ_d reflected back to the reflection output port 15. Other channels having wavelengths $\neq \lambda_d$ may be reflected back to port 15. In effect, the mechanical relay moves the TFF 13a to the position y 19 where the input light of channel λ_d propagates through a clear window of the TFF 13a and exits

from the single fiber output port transmission port 16. For instance, if $\lambda_d = \lambda_1$, The graphical diagrams in FIGS. 8B and 8C show, respectively, that the wavelength λ_1 in channel 1 passes through to the transmission output port 16, and that the wavelength λ_2 in channel 2 and the wavelength λ_3 in channel 3 are reflected back to the reflection output port 15.

FIGS. 9A-9C are graphical diagrams illustrating an example of the reconfigurable dense wavelength division multiplexing device in the blocking state position in accordance with the present invention. With the mechanical relay 18 holding the TFF 13 in the position z 21, all of the channels $\lambda_1, \lambda_2 \dots \lambda_n$ comprising the input optical signal enters the input port 14, through the dual fiber collimator 11, and reflect off the gold film 17a back to the reflection output port 15. In effect, the mechanical relay moves the TFF 13 to the position z 21 where the input light is reflected by the gold film or mirror 17a to the reflection output port 15. The graphical diagram in FIG. 7B shows the waveform for the spectrum measured at port 16 where the input light is blocked such that the intensity of the input light at the transmission output port 16 is near zero or minimum for all wavelengths. The graphical diagram in FIG. 9C shows the waveform spectrum measured at port 15 with the gold film 17a where the intensity is near 1 or maximum for λ_1 in channel 1, λ_2 in channel 2 and λ_3 in channel 3.

FIGS. 10A-10C are graphical diagrams illustrating an example of the reconfigurable dense wavelength division multiplexing device in the transient state position in accordance with the present invention. When the TFFM chip 13 switches from the position y 19 to the position z 21 or when the TFFM chip 13 switches from the

position z 21 to the position y 19, the input beam will need to move through a cross junction between the thin film 13a and the gold film 17a such that the input beam is projected in an area which is between the clearly pass-through state position and the clearly blocking state position. While in this transient state where the mechanical relay
5 18 moves the TFFM chip 13 to the position x 31, it is possible that there could be a beam interruption of the light when the light hits the junction between the gold film 17a and the thin film filter 13a that may affect the intensity of the reflected beam. It is desirable that the thickness of the gold coating is equal to or approximately the same as the reflected light wavelength. The waveforms for the drop spectrum (measured at port 16) and the
10 express spectrum (measured at port 15) in the position x 31 are shown in FIGS. 8A and 8B, respectively.

In one example, a suitable selection of the TFFM chip 13 is a $1.4 \times 1.4 \text{ mm}^2$ four-cavity thin film interference filter. The TFF in the TFFM chip 13 has a designed center wavelength of 1546.12nm with a 25dB stop band of 1nm. The TFF is coated with a
15 1546nm thickness gold layer on one-half of the first face of the TFF. The input port is powered by a broadband source. A first power meter is used to monitor the signal at the transmission output port 16 and a second power monitor is used to monitor the signal at the reflection output port 15.

FIGS. 11A-11C are graphical diagrams illustrating experimental results on the
20 traces of the transmitted and reflected signals in a time domain during transition in accordance with the present invention. The amount of the transmitted signal power and the reflected signal power during the transition are measured using an oscilloscope. An

input light is a c-band wide range light source. FIG. 11A shows that the transmitted power disappears and the reflected power increases by $\delta 1$ while the transition from TFF to mirror occurs and vice versa. In FIG. 11B, it is shown that the transmitted power increases from zero and the reflected power decreases by $\delta 1$ while transitioning from mirror to TFF. The $\delta 1$ can be generated from, for example, the drop signal in channel 2 adds to the total express channel. To quantify the $\delta 1$ parameter, a third experimental data is taken as shown in FIG. 11C. The express power is tested at the position y 19 and there is a placement of a reflecting coated material in front of the TFF to reflect all of the light to the express channel. The parameter δ in FIG. 11C equals to the parameter $\delta 1$ in FIGS. 9A and 9B, which confirms that there is no presence of additional loss during the transition, since there is no indication of any dip in the spectra except for $\delta 1$.

One significant parameter is the insertion loss, which represents the ratio of the input optical signal power to the corresponding output optical signal power. In one example where 100 GHz channel spacing is used, when the filtering area is in the optical path, the measured insertion loss on the transmission is approximately 0.87dB. The 0.5dB passband width is 0.53nm with 0.11dB ripple over the passband. The polarization dependent loss is 0.09dB. The isolation to the adjacent channel is 29dB. On the reflection output port 15, the insertion loss for an express channel is approximately 0.23dB with a loss variation of 0.12dB. The isolation is 16.9dB and the polarization dependent loss is 0.06dB. It is noted that the spectra both for transmission and reflection and the values of the key optical parameters are the same or similar from the TFF devices itself. When the mirror area is in the optical path, the insertion loss over the whole

wavelength range is approximately 0.23dB with a loss variation of 0.11dB. The polarization dependent loss is 0.03dB.

The above embodiments are only illustrative of the principles of this invention and are not intended to limit the invention to the particular embodiments described. For
5 example, one of ordinary skill in the art should recognize that other reflective materials can be used, such as a metal or an oxide, without departing from the spirit of the present invention. Accordingly, various modifications, adaptations, and combinations of various features of the described embodiments can be practiced without departing from the scope of the invention as set forth in the appended claims.